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## PARAMETRIC GENERATION OF ALTERNATING CURRENTS

N. D. Papaleksi

/Figures are appended./

1. There are two basic methods by which mechanical energy can be converted into electrical energy: (a) through the movement of electrical currents in a magnetic field and (b) through the movement of electric charges in an electric field. Both of these methods are used in electromagnetic and electrostatic machines in practice, but the role of the first is immeasurably more important, since electrostatic machines up to this time have been more important as an appurtenance of the physical laboratory than as an engineering tool.

In the first mechanical generators of electrical energy, the magnetic field was constant, and this apparently left its mark upon the further development of electric machine construction.

The principle of self-excitation of dynamos, the so-called Siemens' dynamoelectric principle, which almost completely determined the development of present-day dc and ac electric machines with supplementary excitation, calls for a magnetic exciting field which is constant in time. The generation of direct and alternating currents with the help of a constant magnetic field is very simple and convenient, and this, together with the above-mentioned historical reason, forced electric machine construction almost exclusively into the use of constant fields for excitation. Even in electrostatic machines, self-excitation, of the Toepler-Wimshurst type, for example, or supplementary excitation still involves constant exciting fields.

It is also possible in principle to use alternating magnetic or electric exciting fields for mechanical generation of electric currents. However, this is not as simple as the use of constant fields, since for correct utilization of the laws of induction and mechanical forces, synchronism must be maintained between the movement of the current (or charge) conductors and the field variation. While



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the maintenance of this synchronism for supplementary excitation is difficult (synchronism of phase must also be maintained), it is still more difficult for self-excitation of an ac circuit. A number of designs for self-excitation of an ac circuit have been proposed to solve this problem, e.g., Rudenberg [1], Barkhausen [2], Professor M. V. Shuleykin [3]. In all the above designs, however, the authors circumvented the main difficulty, i.e., maintenance of phase synchronism, by using commutation (collector rings), thereby changing the alternating into a direct process.

The problem of self-excitation of an ac circuit in its purest form can be formulated in the following manner: We have an electrical ac circuit in which there are no apparent sources of emf, i.e., magnetic or electric fields. Can we, by changing only the position of the circuit components, its inductance or capacitance, excite electric currents in it? Obviously, communtation, i.e., changing the dc resistance (conversion of ac into dc) is excluded.

As was theoretically shown by Poincare [4] in 1907, it is impossible to self-excite electric currents in systems without capacitance, in which (during motion) only the inductance changes, providing that communtation is not used. Such self-excitation is possible, however, in special cases with capacitance present when the natural oscillations of the system are used. Rayleigh [5] pointed out this possibility even earlier in connection with similar effects in acoustics (the Melde experiment). Although electrical engineers knew of cases of self-excitation of an ac circuit (for example, an induction generator when the properly selected capacitance is connected into its circuit), these were considered undesirable effects and until recently the problem of self-excitation of an ac circuit had not been studied systematically.

2. The physical side of the effects occurring in self-excitation of an ac circuit can be clarified very simple from the following considerations [11]. Suppose an electrical circuit consists of a capacitance C, inductance L, and dc resistance R (Figure 1). Let the induction coil be constructed so that it admits of a periodic change of inductance (Figure 2) and let an infinitesimal current "i" flow through it at some moment. This infinitesimal current could be obtained as a result of some change inductions, parasitic currents, or atmospheric discharges; in principle it might appear in the circuit even if the whole system were isolated from external effects because of the so-called fluctuations of electrons in the conductors.

Here, in contrast to the case of dynamoelectric self-excitation, the current polarity is not important. Let us assume that at this moment, the inductance of the circuit is changed by $\Delta L$ by an external force. This requires the work $\frac{1}{2} i^2 \Delta L$ and, consequently, the energy of the system is increased by this amount. After this change of the system, we leave it alone. Since the inductance is connected to a capacitance, oscillation will occur if the right conditions prevail in the circuit. After $\frac{1}{4}$ of a period T of natural oscillations of this circuit, all the magnetic energy of the system is converted into electrical energy of the condenser, and the current becomes equal to zero. If at this moment the inductance was decreased to its initial value, no work would be required since no current is flowing. After this operation, we again leave the circuit alone, and then the electrical energy of the condenser will again be converted into magnetic energy, and the current will again increase and reach its maximum after the following 1/4 period of natural oscillations of the circuit. At this time, we can again increase the inductance $\Delta L$, expending some work to introduce energy into the system, and thus again repeat the entire cycle of changes. If in changing the inductance, we have introduced more energy into the system than was expended in charging the condenser, the store of energy in the system will be increased and, consequently, the current strength and the charge on the condenser should be increased with each new cycle. Thus, the oscillations in the circuit will continue to increase and it will be self-excited. A simple mechanical analogy to the above process is the rocking of a swing.

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It is easy to derive the energy conditions necessary for self-excitation of an ac circuit. The losses in the system for one cycle of changing the inductance can be expressed as

$$1/2\ Ri^2 \frac{T}{2},$$

and since the energy introduced into the system during this time is equal to $1/2\ i^2 \Delta L$, the condition for self-excitation is defined by the following inequality:

$$1/2\ i^2 \Delta L > 1/2\ Ri^2 \frac{T}{2},$$

which after a simple transformation reduces

to $$\omega \Delta L > \pi R$$

or $$\frac{\Delta L}{L} > \mathcal{E} \qquad (1)$$

where $$\mathcal{E} = \frac{R}{2L} \quad T\ (1_1)$$

is the logarithmic decrement of the system's oscillations.

The dependency (1) can be written in the form:

$$m > \mathcal{E}/2,$$

where $$m = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad (2)$$

is the so-called "percentage modulation" of the inductance.

Thus, if we change the inductance with a frequency which is approximately twice that of the natural frequency of the system, then when the relative magnitude of the change of inductance is greater than a definite value which depends on the damping of the natural oscillations of the system, an alternating current should emerge and increase in the system. The frequency of this alternating current will be approximately equal to the natural frequency of the system, i.e., it will be close to half the frequency of the change of inductance. Obviously, these considerations also apply to the case when the capacitance is changed in the circuit.

The simple considerations above show that with a periodic change of one of the parameters of the oscillatory circuit (capacitance or inductance) and observance of the condition ($1_1$) (as closer inspection shows, the condition ($1_1$) takes on the form

$$m > \frac{2\mathcal{E}}{\pi} \text{ or } \quad \omega \Delta L > 4R \qquad (3)$$

for the case of a harmonic change of the parameter), ever-increasing currents must emerge in the circuit, i.e., the circuit will be self-excited. If the parameters of the system are left constantly independent of the currents or voltages, or, in other words, the system is left linear (i.e., can be described by linear differential equations), the current or charge would continue to increase without limit until the insulation of the system broke down or the power of the motor rotating the variable inductance (or capacitance) became insufficient.

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A stationary state could not be established in such a "linear" system and consequently it could not become a current generator. To do this, we must introduce into the system factors which depend on the current and which will limit its further increase. Only then can we obtain a stationary state and produce an alternator. This is completely analogous to dynamos with the usual self-excitation, in which the stationary state is also provided by the "nonlinearity" of the magnetization curve for iron.

Since self-excitation in our case is provided by a change of a parameter of the system, it has been given the name "parametric," and generation based on it is called parametric. We especially emphasize that the frequency of the alternating current generated is exactly equal to half the frequency of the parameter change, so that we deal here with a synchronous electric machine.

From the above, it is clear that the problem of parametric generation of alternating current is inseparably connected with the problem of self-excitation of an ac circuit, which in turn is connected in principle with the excitation of oscillations by a periodic change of the parameters of the oscillatory system. This last very important problem has recently attracted the interest of many researchers [6, 7, 8, 9, 10, 15], both in the Soviet Union and abroad. Beginning in 1927, it has undergone systematic theoretical and experimental development by a number of workers under the direction of Academician L. I. Mandel'shtam and the author in the Scientific-Research Institute of the first Moscow State University, the former Central Radio Laboratory, the former Leningrad Electrophysical Institute, and then in the Leningrad Industrial Institute. As a result of these works [10, 11, 12, 13, 14], effects of parametric self-excitation in an ac circuit were obtained for the first time using a periodic mechanical change of both inductance [10] and capacitance [11] in the absence of any apparent sources of electric or magnetic fields (exciters, storage batteries, permanent magnets, etc.). In addition, a theory of the processes was developed (self-excitation conditions, magnitude of stationary amplitude, etc.).

Naturally, the establishment of a new principle of self-excitation of alternating current has pushed the problem of using it for generation of alternating currents to the forefront.

[Sections 3 and 4 are omitted here. They deal with a theoretical treatment of the nonlinear differential equations to which, according to the author, the theory of parametric generation of alternating current reduces.]

5. In conformance with the two possible methods of parametric generation, namely, periodic change of inductance or capacitance, there can be two essentially different new types of electric machines which we shall distinguish (a) the "inductive" parametric alternator (PMI) and (b) the "capacitive" parametric alternator (PMYe).

In the first case, we deal with a synchronous electric machine, externally similar to machines of the normal inductor type, the only essential differences being that, on one hand, there are no exciting windings, a fact which is very important in design, and, on the other, capacitance is required. Therefore, there is no doubt about the possibility of obtaining power of the same order as from ordinary alternators from the "inductive" parametric alternator. The chief interest in work with inductive parametric alternators lies in determining to what degree and under what conditions the new principle of parametric self-excitation might prove useful and advantageous in practice. This new principle makes exciting windings unnecessary, but also carries the condition that the ac circuit must be oscillatory and approximately tuned in resonance to half the frequency of the inductance change, i.e., it makes capacitance necessary.

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These facts force us to assume that the region of high frequencies would be especially advantageous for parametric alternators, since the absence of rotor windings permits the use of high angular velocities, while the cost and size of the condensers required for tuning to resonance are decreased with an increase of frequency. On the basis of these considerations, an experimental model of a 1-kw, 600-cycle, 3,000-rpm alternator was designed with the help of Engineer M. M. Verbitskiy and successfully produced in the shops of the Leningrad Industrial Institute. The rotor of the alternator is a duraluminum disk, on the periphery of which are placed 24 blocks of iron, each separated by layers of insulating material. The stator in turn consists of 24 open magnetic circuits encompassing one common winding placed symmetrically on the periphery. When the rotor turns, the magnetic circuits of the stator are alternately closed and open, which provides a periodic change of the circuit inductance.

Tests made by scientific workers A. G. Rzyakin and A. M. Martynov of the parametric machines group, aided by mechanic P. K. Loncha, showed that when self-excitation conditions were fulfilled (obtained by tuning the circuit to the desired frequency by connecting the proper capacitance in the circuit), the alternator was excited and could produce power of one kw at an efficiency of about 70% for prolonged periods. A number of characteristics of this alternator are given in Figure 4 and an oscillogram of the current in one case is shown in Figure 3, b.

Among the interesting design features of this alternator are its low weight (about 15 kilograms without the base), low copper weight (0.76 kilograms) and a low "machine constant"

$$C = \frac{D^2 \, l \, n}{kw} = 18^2 \cdot 3.2 \cdot 3000 = 31 \cdot 10^5.$$

Testing revealed that some parts could be improved, which would result in increased efficiency and lower alternator weight.

On the basis of data obtained in the production and testing of this experimental model, a more powerful model of a parametric alternator (40-60 kva, 1,600 cycles, 3,000 rpm) was designed with the help of Engineer M. M. Verbitskiy and Professor A. A. Alekseyev. This alternator design was given to the "Elektrosila" Plant imeni Kirov for production.

The characteristics of inductive parametric alternators indicate that it can best be used in those branches of engineering where high frequencies (500-2,000 cycles) are necessary or advantageous, e.g., for supplying induction furnaces and vacuum-tube radio transmitters, and also wherever a high dc voltage is required (this would be obtained by rectifying the ac voltage generated by the parametric alternator). Since capacitance is necessary in all these cases, the condenser used as an integral part of the parametric alternator is not excess baggage from the standpoint of increasing the size, weight, and cost. The more powerful inductive parametric alternator now under construction is designed for supplying induction furnaces.

Along with all the structural advantages gained by the use of the parametric principle of self-excitation which eliminates the exciting windings, the need for a magnetic field exciter is eliminated. This fact, which is of little importance in ordinary high-power synchronous machines, may prove very advantageous with respect to weight, size, and cost for small generators, especially when the problem of reducing weight is very important. In addition, the problem of the condenser is much more easily solved in the generation or low power.

6. The second possible method of parametric generation of alternating current was implemented in the so-called "capacitive" parametric alternator (PMYe). Here we deal with a synchronous electric machine, in which mechanical work is transformed into electrical energy by a periodic change of the capacitance connected in the oscillatory circuit, the latter being tuned to approximately half the frequency of the capacitance change. The basic part of this alternator is the variable capacitance, which can be made in the same way as the rotating variable condensers used in radio engineering in the form of a collection of stator and rotor plates of the proper form, so designed that when the rotor turns with the desired speed the capacitance changes within wide limits from $C_{max}$ to $C_{min}$.

The capacitive parametric alternator is so different essentially from ordinary electric machines that electrical engineers will first of all doubt whether power of the order in which they are interested can be obtained from it. Actually, the power $P_c$ which can be generated by changing the capacitance of the oscillatory circuit according to the law:

$$C^{-1} = C_o^{-1} \cdot (1 + m \cdot \cos 2\omega t)$$

is expressed as

$$P_c \approx -\frac{m\omega}{C_o} \cdot \frac{1}{T} \cdot \int_o^T q^2 \sin 2\omega t \cdot dt,$$

so that with a harmonic change of current we will have in the best case

$$P_c = \frac{1}{2} \; m w q_o^2 / 2C_o \approx \frac{1}{4} \; m w C_o \; U^2 max \qquad (17)$$

from which it follows that the power which can be generated will be the greater, the higher the frequency $\omega$, the greater the percentage modulation of the capacitance m, and the greater the energy in the condenser

$$1/2 \; C_o U^2_{max}.$$

Thus, the problem of generating high power depends on the possibility of accumulating sufficient energy in the variable condenser. Since it is impossible in practice to construct a condenser which would have high capacitance and still permit rapid changes in capacitance over wide limits, the only possible method of solving this problem, as is seen from formula (17) for $P_c$, lies in increasing the voltage $U_{max}$. However, the dielectric strength of air under normal conditions (30,000 v/cm) is far too low to obtain any degree of power.

To illustrate, we calculate the power which can be obtained from an experimental model of a capacitive parametric alternator. The stator of the variable condenser, which is the main part of the alternator, consists of 26 disks with diameter 28.5 cm, each divided into 16 sections, while the rotor has 25 such disks. Adjacent disks are 2 mm distant and thus

$$C_{max} = 6420 \text{ cm, while } C_{min} = 3860 \text{ cm},$$

whence

$$C_o = 1/2 \; C_{max} + C_{min} = 5140 \text{ cm and } m = 0.25.$$

For 3,000 rpm, the frequency of capacitance change is $2\omega = 5{,}000$ cycles. Taking as the permissible voltage $U = 5{,}000$ v, we obtain for the power:

$$P_c = 22.4 \text{ w},$$

a negligible quantity from the standpoint of power. The only method by which the power can be increased is to increase the permissible voltage, i.e., to [redacted] 50X1-HUM

increase the dielectric strength of the medium. There are two ways in which this can be done. One of these is to place the variable condenser in a gaseous medium under high pressure. Since the breakdown voltage of gases, wherever Paschen's law holds, increases with an increase of pressure p as a function of pd (where d is the distance between electrodes or, in our case, between adjacent condenser plates), it is possible by increasing the pressure to increase the working voltage $U_{max}$. For example, if the pressure is increased to 20 atm, the breakdown voltage is increased 16 times, and consequently the power is increased approximately 250 times (for the same safety factor). Therefore, under these conditions, our model of a capacitive alternator would generate about 5.6 kw, a value already of interest for engineering. Even higher voltages could be obtained with a further increase of pressure.

According to I. M. Gol'dman's recent data [20], gases under pressures of 70-80 kg/sq cm can sustain voltage gradients up to $10^6$ v/cm. This would permit us to obtain power of the order of 22 kw from the model capacitive alternator considered. If we use this data as a basis, calculation shows that it is possible to construct capacitive parametric alternators producing high power (tens of thousands of kilowatts) whose size would not exceed that of the ordinary high-power alternators. We should keep in mind, however, that the quantitative data cited for breakdown voltages at high pressures applies to experiments with gases at rest, while in the capacitive parametric generator we deal with breakdown voltages in a gaseous medium which is in very rapid random motion. In addition, we also have here a nonuniform electric field which, according to available data [22], may substantially affect the permissible voltages.

To clarify experimentally how all these factors affect the dependency of the working voltage on pressure and to what degree the pressure increase could be used to increase the power of the capacitive parametric alternator, we constructed an experimental model of a variable condenser and rotated it in a medium under high pressure. The stator of the condenser is its system of fixed plates while the rotor is its system of movable plates. Since the plates of the stator and rotor have 16 sections, each symmetrically spaced along the periphery, at 3,000 rpm the frequency of the capacitance change is 800 cycles and, consequently, the frequency of the alternating current generated is 400 cycles. The condenser was placed in a steel casing into which dry air could be pumped with the aid of a compressor.

To fulfill the self-excitation conditions for the variable condenser, a coil with inductance L equals 27.4 h was connected in the circuit. This coil was selected to tune the circuit consisting of the condenser, the coil, and the load resistance to resonance at a frequency of about 400 cycles. The schematic diagram of the generator is shown in Figure 5. C denotes the variable condenser described above, F is a spherical discharger connected in parallel with C, L is the coil for tuning the circuit to resonance at the desired frequency, $R_1$ is a lamp rheostat, and $R_2$ is a rheostat of the Rustrat type. Since the logarithmic decrement of the circuit without load was equal to 0.035, and the experimentally measured modulation factor m was equal to 0.34, the generator was easily self-excited and a high load resistance could be used.

The results of some measurements made by A. G. Rzyankin and A. M. Martynov showed that the breakdown voltage in the variable condenser increased smoothly and continuously with the increase of gas (air) pressure when the rotor turned at 3,000 rpm. Thus, the working voltage of the generator and consequently its power also could be increased. Because of poor packing at the point where the rotor shaft left the casing, the pressure could not be increased above 12-13 kg/sq cm; in addition, low accuracy in the production of the condenser plates and in their assembly considerably reduced the breakdown voltage. The useful power obtained at a pressure of 12.5 kg/sq cm was about 560 w at a voltage $U_{max} \approx 21$ kv. The electrical efficiency was above 92%. At the same time, measurements were made of the mechanical losses as a function of the pressure in the medium containing the rotating condenser. An oscillogram of the current produced by this generator is shown in Figure 3, a.

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7. While the experiments made with the laboratory model of a capacitive parametric alternator showed that the power generated increases with increased gas pressure and that, consequently, considerable power could be generated by following this method, they also underscored the fact that the pressure increase was unavoidably accompanied by an increase in mechanical losses and also by liberation of heat within the condenser when the condenser rotor turned in an atmosphere of compressed gas. The last factor not only reduced the efficiency of the generator, but also required special measures to draw off the heat liberated. The use of a gaseous medium under high pressure, therefore, did not prove technically advantageous. Various methods could be employed for the solution of this problem; we could, for example, try to use gases or vapors of technical substances whose dielectric strength is considerably higher than that of air. On the other hand, we could give most of our attention to decreasing losses in the rotation of the condenser, using for this purpose a gas with a considerably lower specific weight than air. Even more important, we could try to find methods which would allow us to recover partially the energy released in the compressed gas in the form of heat.

A method suggested by Academician L. I. Mandel'shtam and the author called for the use of superheated steam as the gas under high pressure, the specific weight of which is considerably less than the specific weight of air (for example, at pressure of 20 atm and a temperature of $350^{\circ}$ C, the specific weight of steam is only 1/3 the specific weight of air for the same pressure and a temperature of $20^{\circ}$ C), and the use of a steam turbine as the motor driving the variable condenser. The superheated steam would enter the turbine from the chamber in which the variable condenser is located. This would be advantageous, in that (a) the losses in driving the condenser would be considerably lower than in air, and (b) the heat liberated in the condenser would be used to heat the steam and thus the energy expended in it would be almost completely recovered.

An important prerequisite for this solution was that the superheated steam have sufficient dielectric strength. Since there was no available data on this problem, we had to set up special investigations. According to the preliminary results obtained by A. G. Rzyankin [23], the dielectric strength of steam at pressures of about 10 kg/sq cm was no less than that of air, other conditions being equal. Since a preliminary study of the feasibility of the steam-turbine capacitive-parametric-alternator combination had already given promising results both from the standpoint of efficiency and design, this method of creating a capacitive parametric alternator seemed quite possible.

However, there still remained a number of design difficulties, connected mainly with the problem of satisfactorily tapping the high voltage from the steam chamber in which the rotating condenser is located. The potentialities and regions of application opened by this method can be judged decisively only after proper preliminary studies are made and laboratory models tested.

8. Another possible method for increasing the power of the capacitive generator by increasing the permissible voltage is to use a vacuum as an insulator. A vacuum is in many respects an ideal insulator, and therefore engineers and physicists have long searched for ways to solve this problem both here (Academician N. N. Semenov) and abroad (the Metro-Vickers Laboratory and others). Until recently, however, this problem remained unsolved. The maintenance of a sufficiently high stable vacuum in a medium containing large masses of metal was an especially difficult task in practice, especially when these large masses move at high speed (as is the case in electrical machines). The results of recent works [18, 19] on the use of a vacuum as an insulator give reason to believe that this problem has already passed from the stage of pure laboratory studies to the field of practical engineering use. The 100-kv electrostatic generator in a vacuum (power of 2 kw) constructed by Trump, operating on the ordinary electrostatic machine principle, shows that a high-power capacitive parametric alternator using a vacuum as an insulator is feasible.

Judging from the voltage gradients in a vacuum (up to $1.1 \cdot 10^6$ v/cm) obtained by Trump /19/, it seems possible to design a capacitive parametric alternator which will compare in power with ordinary alternators. The advantages to be gained by using a vacuum as an insulator are tremendous, e.g., there will be no losses in the dielectric, no mechanical losses in rotation, no need for drawing off heat, etc. All of these will undoubtedly increase the efficiency and in addition will be very beneficial from the design standpoint.

Another advantage of a vacuum in the capacitive generator is the possibility of obtaining very high, almost maximum, efficiencies (above 99%). Moreover, the electric losses in the variable condenser in a vacuum or an atmosphere of compressed gas will remain low even when the frequency is increased, so that the efficiency can be made very high even for capacitive alternators operating at higher frequencies. Since the power of the capacitive alternator is proportional to the frequency, its most efficient application will be in the high-frequency field.

During operation of the generator, a constant stable vacuum (or a constant vapor or gas pressure) must be maintained in it, and this requires special equipment (air pumps, compressors, steam generators, etc.,), the importance of which with respect to weight, size, and need for additional power will decrease as the power of the generator itself is increased. Therefore, the capacitive generator, in contrast to the inductive generator, will be more advantageous the greater its power.

We should note that in the capacitive generator the voltage on the variable condenser, and consequently on the coil connected in series with it, is much greater than the voltage of an ordinary alternator of the same power. Therefore it might be considered as a combination of an alternator and a step-up autotransformer. This must be taken into consideration when the capacitive alternator is compared with ordinary alternators from the standpoint of technology and economics.

Because very high voltages are generated simultaneously with high power in capacitive parametric generators, they may be of importance for long-distance power transmission. In this case, the fact that it is possible and even more advantageous to generate very high power in the form of high-frequency currents is very important. Since high frequencies present a number of advantages for conversion of ac into dc, it is possible that high-power capacitive parametric generators might be preferred over ordinary alternators as sources for long-distance power transmission.

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/Appended figures follow:/



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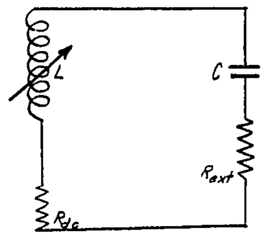


Figure 1. Equivalent Circuit of the Inductive Parametric Generator

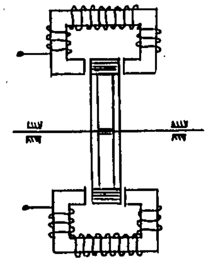

Figure 2. Variable Inductance

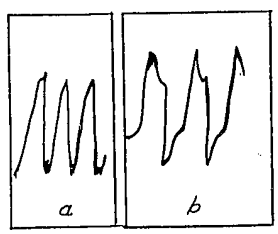


Figure 3. Oscillogram of Current Obtained From (a) Capacitive and (b) Inductive Parametric Generators

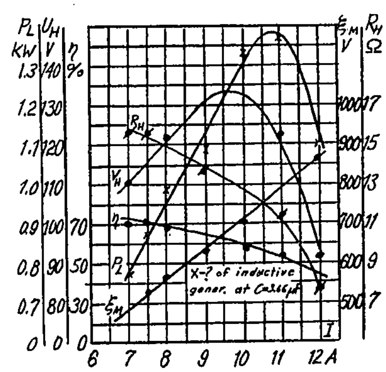


Figure 4. Characteristics of Inductive Parametric Generator

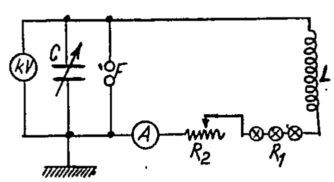


Figure 5. Equivalent Circuit of Capacitive Parametric Generator

- E N D -